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ON THE NATURE OF AURAL HARMONICS[1]

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The common observation that stimulation of the ear by purely sinusoidal wave gives rise to the perception of aural (subjective) harmonics is generally ascribed to the non-linear and asymmetrical characteristics of the ear, viewed as an electro-mechanical transducer. Estimates of the magnitudes of aural harmonics have been made by indirect means (Fletcher[2]), and are such as to indicate a high degree of distortion for tones of great intensity.

It can be shown that the motion of a system under an impressed sinusoidal force will not be sinusoidal unless the system obeys Hooke's law, i.e., unless the displacement is proportional to the applied force. In general, the resulting motion in a non-linear system can be described in terms of a Fourier series. However, if the departure of the system from linearity (Hooke's law) is symmetrical in both directions from the position of rest, the Fourier series will contain only odd terms. Thus in the analogous case of electronic vacuum-tubes connected in "push-pull," there is present in the output circuit only the fundamental frequency and its odd harmonics. On the other hand, if the system is not symmetrical on either side of the operating point (position when no force is applied) even as well as odd harmonics will be present in the resulting motion. An analogous case, for example, is found when "push-pull" arrangement is unbalanced.

Now, it is clear that the aural harmonics contain both odd and even components. The problem, then, is to account for them in terms of non-linearity and of asymmetry.

In order to observe the aural harmonics directly, we examined the electrical potential generated in the cochleas of animals. Between a pair of electrodes, one in contact with the round window of the cochlea and the other in contact with the muscles of the neck, one obtains an electrical potential, presumably generated by the hair cells of the organ of Corti (Stevens and Davis[3]), which appears to be directly proportional to the distorting force to which the hair cells are subjected. We amplified these potentials and led them to a cathode-ray oscillograph and to a wave-analyzer (General Radio, type 636A). Then, on stimulating the ear with pure tones of various frequencies and intensities, the behavior of the aural harmonics could be observed under various conditions.

Typical results for a cat, under dial anesthesia, are shown in figure 1. The relative magnitude of the electrical response at the fundamental frequency of 1000 cycles and of each of the harmonics was measured by the wave-analyzer for various sound intensities. The harmonic content (2nd) of the stimulating tone was less than 0.5%, an amount which means that it was negligible in comparison to the size of the aural harmonic. It will be noted that the second harmonic makes its appearance at about 40 db above threshold and increases rapidly in size, up to the point at which the fundamental approaches its maximum. Then the second harmonic decreases, while the third continues to grow until it finally exceeds the second.

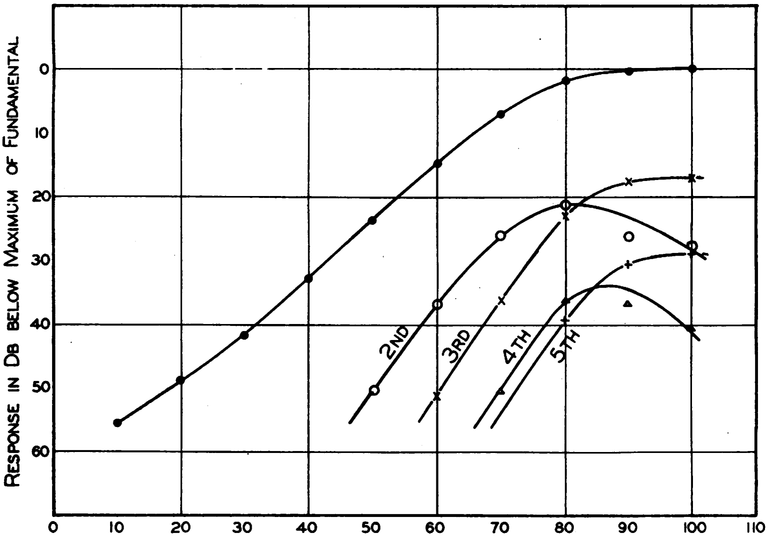

FIGURE 1

Analysis of the cochlear response of a cat when stimulated with a pure tone of 1000 cycles. Abscissa values represent the intensity of the stimulus in decibels above the human threshold. The ordinate scale is in decibels below the maximum value of the fundamental. The uppermost curve shows the magnitude of the fundamental in the response when the ear is stimulated with sound intensities plotted along the abscissa. The other curves in order show the magnitude of the second, third, fourth and fifth harmonics. Thus the intersections along any given vertical line give the relative magnitudes of the first five partials in the response when the ear is stimulated with a given tone.

A similar relation obtains between the fourth and fifth harmonics. In general, the even harmonics pass through a maximum, whereas the odd harmonics appear not to decline.

The same effect is shown in figure 2 for the case of a guinea pig. Nor is this result peculiar to tones of 1000 cycles. All frequencies show the same phenomenon, within our ability to measure them. At low frequencies the relations are complicated by the presence of anomalous effects due to action currents (presumably from the auditory nerve). These action potentials distort the appearance of the cochlear potential in an unpredictable fashion. At frequencies of 1000 cycles and above, the action potentials produce negligible effects.

The evidence indicates that, after taking account of the sensitivity of the ear at all frequencies, the magnitude of the harmonics in the cochlear response of cats and guinea pigs bears a constant relation to the magnitude of the fundamental, as defined by its maximum value. Thus the second harmonic of a 650-cycle tone appears larger, relative to the fundamental, than that of a 5000-cycle tone, but, of course, the ear is more sensitive to the second harmonic of 650 cycles than it is to that of 5000 cycles. After

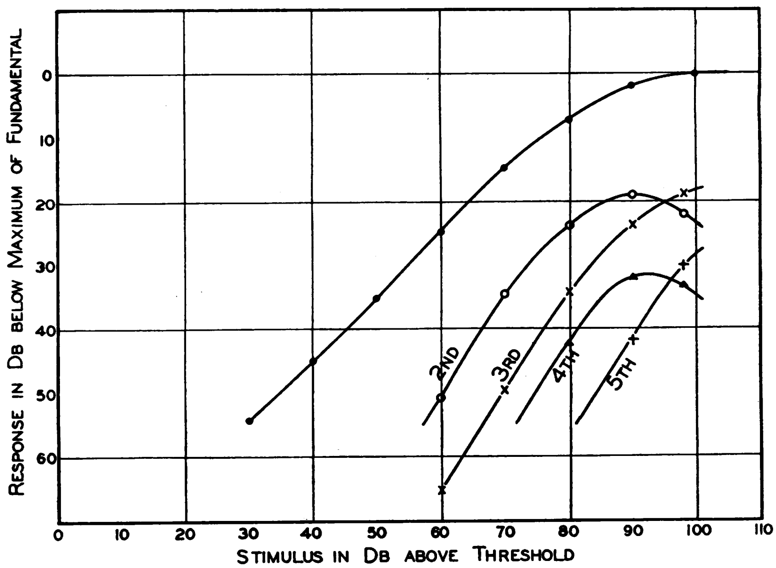

FIGURE 2

Curves for the guinea pig—similar in all respects to those for the cat in figure 1.

making the proper adjustments, we find that, to a first approximation, the aural harmonics, at all frequencies, depend in identical fashion upon the form of the curve relating the size of the fundamental to the intensity of the stimulus. (Measurements were actually made at frequencies of 150, 200, 370, 650, 1000, 1750, 2500 and 5000 cycles.)

It is clear from figures 1 and 2 that the behavior of the even harmonics differs from that of the odd. The odd harmonics appear to arise when the amplitude of motion approaches the elastic limits of the auditory mechanism. The presence of even harmonics must mean that this limit is reached more quickly in one direction than in the other. These considerations suggest that altered tensions on the transmission apparatus of the middle ear could affect the magnitude of the even, but not of the odd, harmonics.

The guinea pig, under a proper dose of dial, shows a convenient disposition to contract its tensor tympani spasmodically. The presence of these contractions indicates a certain functional tonus in the muscles of the middle ear. Deeper anesthesia abolishes these contractions, and decreases the tonus correspondingly (Stevens, Davis and Lurie[4]). By measuring the harmonic content of the cochlear response before and after abolishing the muscle tonus, its effect can be readily measured. Figure 3 shows that alteration of the tension in the tensor tympani produced a marked decrease in the amount of second harmonic, but left the third harmonic unchanged. Similarly, the fourth decreased and the fifth remained unaltered. Hence it appears that the even harmonics are amenable to experimental control through factors which alter the symmetry of the auditory mechanism.

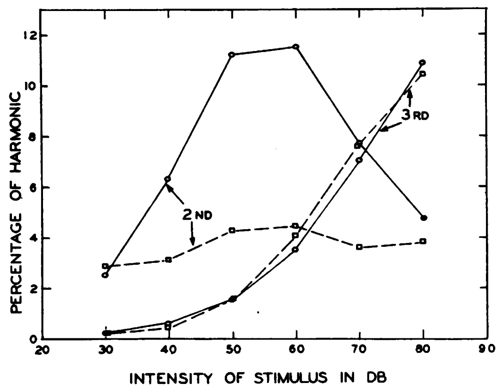

FIGURE 3

Effect of changed tonus of the muscles of the middle ear upon the magnitude of the second and third harmonics. Each curve is an average of values for 1000, 1750 and 2500 cycles. The ordinate scale gives the harmonic content of the response as a percentage of the fundamental. The abscissa represents the intensity of the stimulus referred for each frequency to the intensity necessary for 0.1% of the maximum response of the fundamental. The two bell-shaped curves are for the second harmonic; the sigmoid curves are for the third harmonic. The difference between the dashed bell-shaped curve and the solid curve indicates the change in the second harmonic following relaxation of the muscles of the middle ear. The dashed sigmoid curve shows the almost imperceptible alteration of the third harmonic following this same change. The data is for the guinea pig represented in figure 2.

Finally, we can construct an approximation to the over-all characteristic curve of the ear. To do so, we plot the curve for the response of the fundamental (Fig. 1) in linear instead of logarithmic coördinates. It should be noted that the long linear portion of the former curve is now properly represented as a small segment very near the operating point. The resulting curve represents the upper half of the characteristic curve, as shown in figure 4. The lower half is simply an image of the upper half. Now, if the ear were symmetrical, the position at rest (the operating point) would be at 0. Tension in the muscles of the middle ear, plus other secondary factors, tend to displace the operating point to position A. Then, any sinusoidal force operating about point A will produce a motion having odd and even harmonic components.

From this picture it is clear why the even harmonics in figures 1 and 2 pass through a maximum. When the system is forced to its elastic limit,

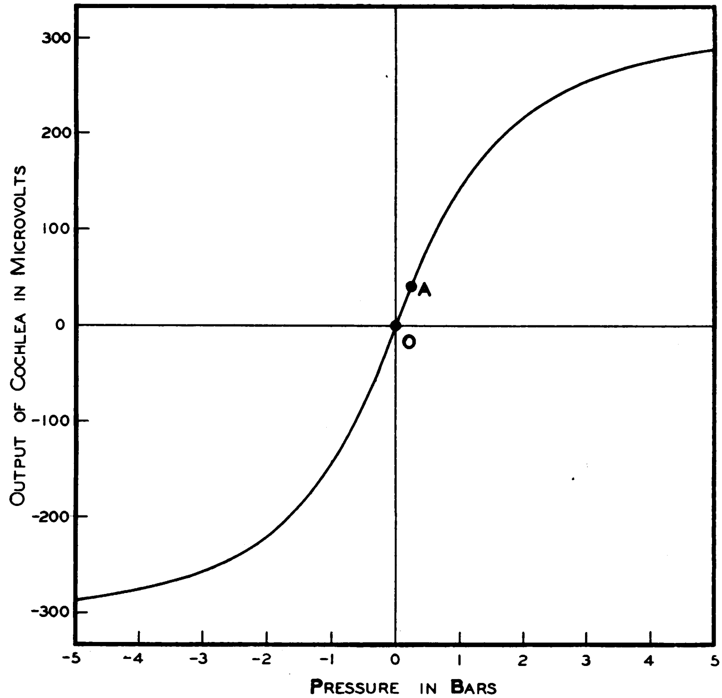

FIGURE 4

Approximate characteristic curve of the ear. The curve relates the electrical output of the cochlea (ordinate) to the applied sound pressure (abscissa). Thus, when the pressure varies sinusoidally about the zero value, the instantaneous voltage in the cochlea can be read from the curve and the resulting wave form determined. When tension in the muscles of the middle ear upsets the symmetry of the curve, it is equivalent to shifting the operating point (point corresponding to zero pressure and zero voltage) from O to A. With the operating point at A both odd and even harmonics are present in the output wave.

so that the cut-off at the two ends becomes more similar, the "wave form" of the resulting motion becomes more symmetrical, which in turn signifies a relative decrease in the even harmonics.

[1] These experiments made use of the combined facilities of the Psychological Laboratory, Harvard University, and the Department of Physiology, Harvard Medical School.

[2] H. Fletcher, "A Space-time Pattern Theory of Hearing," *Jour. Acoust. Soc. Amer.*, **1**, 311–343 (1930).

[3] S. S. Stevens and H. Davis, "Psychophysiological Acoustics: Pitch and Loudness," *Jour. Acoust. Soc. Amer.*, **8**, 1–13 (1936).

[4] S. S. Stevens, H. Davis and M. H. Lurie, "The Localization of Pitch Perception on the Basilar Membrane," *Jour. Gen. Psychol.*, **13**, 297–315 (1935).